

The following notice applies to any unclassified (including originally classified and now declassified) technical reports released to "qualified U.S. contractors" under the provisions of DoD Directive 5230.25, Withholding of Unclassified Technical Data From Public Disclosure.

NOTICE TO ACCOMPANY THE DISSEMINATION OF EXPORT-CONTROLLED TECHNICAL DATA

- 1. Export of information contained herein, which includes, in some circumstances, release to foreign nationals within the United States, without first obtaining approval or license from the Department of State for items controlled by the International Traffic in Arms Regulations (ITAR), or the Department of Commerce for items controlled by the Export Administration Regulations (EAR), may constitute a violation of law.**
- 2. Under 22 U.S.C. 2778 the penalty for unlawful export of items or information controlled under the ITAR is up to ten years imprisonment, or a fine of \$1,000,000, or both. Under 50 U.S.C., Appendix 2410, the penalty for unlawful export of items or information controlled under the EAR is a fine of up to \$1,000,000, or five times the value of the exports, whichever is greater; or for an individual, imprisonment of up to 10 years, or a fine of up to \$250,000, or both.**
- 3. In accordance with your certification that establishes you as a "qualified U.S. Contractor", unauthorized dissemination of this information is prohibited and may result in disqualification as a qualified U.S. contractor, and may be considered in determining your eligibility for future contracts with the Department of Defense.**
- 4. The U.S. Government assumes no liability for direct patent infringement, or contributory patent infringement or misuse of technical data.**
- 5. The U.S. Government does not warrant the adequacy, accuracy, currency, or completeness of the technical data.**
- 6. The U.S. Government assumes no liability for loss, damage, or injury resulting from manufacture or use for any purpose of any product, article, system, or material involving reliance upon any or all technical data furnished in response to the request for technical data.**
- 7. If the technical data furnished by the Government will be used for commercial manufacturing or other profit potential, a license for such use may be necessary. Any payments made in support of the request for data do not include or involve any license rights.**
- 8. A copy of this notice shall be provided with any partial or complete reproduction of these data that are provided to qualified U.S. contractors.**

DESTRUCTION NOTICE

For classified documents, follow the procedure in DoD 5220.22-M, National Industrial Security Program, Operating Manual, Chapter 5, Section 7, or DoD 5200.1-R, Information Security Program Regulation, Chapter 6, Section 7. For unclassified, limited documents, destroy by any method that will prevent disclosure of contents or reconstruction of the document.

The Bekker Model Analysis for Small Robotic Vehicles

Grant R. Gerhart

US Army TACOM, Warren, MI 48397/ATTN: AMSTA-TR-R/MS 263

Copyright © 2004 SAE International

ABSTRACT

This paper uses the Bekker model for land locomotion analysis to compare ground vehicle vehicles with different running gear configurations. The Bekker model is inherently phenomenological in nature and requires empirical data to both calibrate and validate the methodology for realistic soil/terrain conditions. This formalism consists of two fundamental equations. The first uses the Coulomb-Mohr law and a linear, one degree of freedom spring/mass/damper model to predict terrain shear rates from maximum vehicle tractive effort. The second empirically predicts soil sinkage as a function of ground pressure loading. The latter contains no phenomenological link to the continuum mechanics of terrain materials and conditions.

INTRODUCTION

Bekker's formalism was developed as a design tool to compare different types of ground vehicle mobility performance characteristics. No single vehicular locomotion system has optimal mobility performance under all terrain conditions. Vehicle running gear design always involves design compromises or tradeoffs over a number of mobility factors. Most future Army robotic vehicle platform concepts fall into two broad categories: wheeled and track systems.

Wheeled vehicles are typically more agile and maneuverable than tracked vehicles, but possess higher ground pressure levels and therefore are less mobile over rough terrain. Tracked vehicles on the other hand have lower ground pressure, superior traction and are thus more trafficable for off-road conditions. However, they are not as agile or mechanically efficient as their wheeled counterparts due to

(typically) larger mass and much larger internal motion resistance.

Both wheeled and tracked vehicles have been successful in negotiating roadways and moderately unstructured off-road terrain. Vehicles with a larger wheelbase, ground clearance and horsepower per weight ratios generally have much better intrinsic mobility performance than smaller systems. A comparison of vehicle types for equal size and weights indicates that wheeled systems are typically superior to track systems in agility, maneuverability, ride quality and terrain damage. Tracked vehicles have distinct advantages relative to stability, ground pressure, maximum vertical slope, and drawbar pull.

Selection of running gear configuration usually becomes a choice between which mobility characteristics are most important for a vehicle's intended mission profile. Ride quality is not important to unmanned or robotic vehicles unless payloads such as sensor systems or structural loading specifications are exceeded for rough terrain conditions. The vehicle need only have sufficient drawbar pull to transport itself and its payload. Low ground pressure is principally an advantage only in soft soil terrain conditions. Unmanned systems generally weigh less and have a lower ground pressure than the larger manned combat vehicles such as the main battle tanks or infantry fighting vehicles.

Agility and maneuverability are both advantageous for off-road conditions. Ground clearance, maximum slide slope angle and wheelbase are important for difficult obstacle negotiation challenges such as ditch crossings or large vertical steps. In general a complete systems analysis is necessary to determine the

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 29 JUL 2004		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE The Bekker Model Analysis for Small Robotic Vehicles				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Gerhart, Grant R				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) USA TACOM 6501 E Mile Road Warren, MI 48397-5008				8. PERFORMING ORGANIZATION REPORT NUMBER 16116	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Distribution authorized to U.S. Gov't. agencies only; (Critical Technology; 1/5/07). Other requests shall be referred to (TARDEC).					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 9	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

optimal set of mobility characteristics for a particular mission profile. Unmanned vehicles in particular need a new set of system requirements and represent a separate set of design challenges as compared to their traditionally manned counterparts.

THE BEKKER MODEL

The mechanical behavior of soils varies considerably under a wide variety of environmental conditions. For example composition, moisture levels, porosity, temperature, etc., affect bulk soil mechanical behavior relative to vehicle/terrain dynamics. It is also well known that for the same amount of mechanical loading, a tracked vehicle may cross soft terrain without considerable slippage, whereas wheels may slip significantly, or simply sink into the terrain. The amount of slip varies with soil type.

The Bekker model uses the relationship between certain physical soil characteristics and shearing strength to predict vehicle cross-country mobility. Bekker considers wheels and tracks as simple loading surfaces having similar forms, but different lengths and widths. He extrapolates the analogy between soil shear produced by laboratory crawlers to track vehicles as shown in Fig. 1a [1]. When the blocked track is moved relative to the soil mass in the laboratory shear box, the maximum shearing force is not developed instantaneously with the initiation of relative motion. Instead the soil must be compacted to some degree before reaching the final steady state mechanical shearing stress. Thus the track grousers begin slipping before reaching the point of maximum vehicle traction. This transient condition is the basis for Bekker's simple 1-DOF model for vehicle trafficability.

The shear stress is the ratio between the vehicle traction force, which is parallel to the soil surface, and the area of the track normal to the surface. This tractive force is opposed by soil resistance as the grousers slip during the shearing process. The normal loading force of the vehicle compacts the soil, which affects the resistance it exerts against the track grousers as they push against the ground. In summary the track pushes against the soil, generates tractive forces that are determined by mechanical properties of the medium.

The shear stress is the ratio between the vehicle tractive force, which is parallel

to the soil surface, and the area of the track normal to the surface. This force is opposed by the soil resistance when the

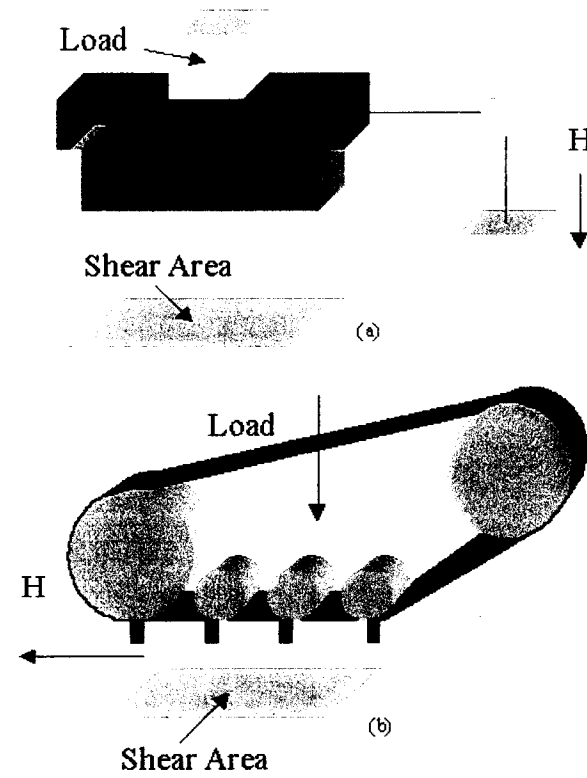


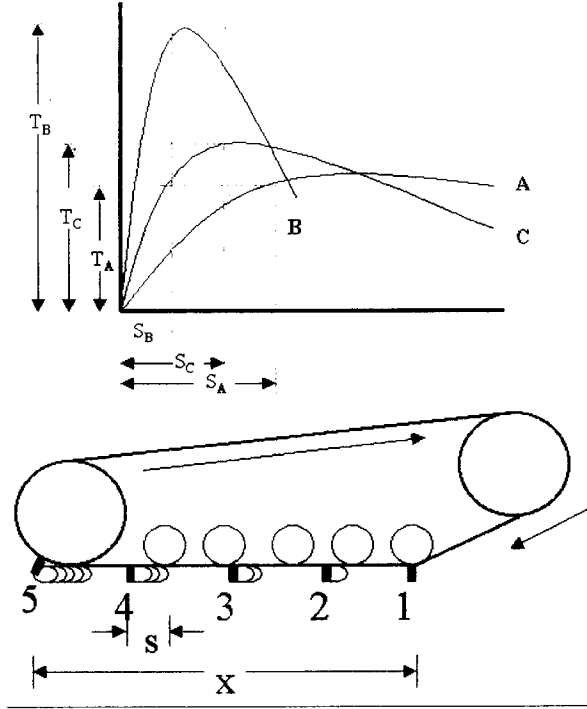
Figure 1 Soil Shear Analogy

vehicle weight compacts the soil and also affects the resistance it exerts against the grousers. In effect the track forces, which push against the soil, generate a soil resistance that is determined by soil type and compaction. Vehicle weight generates ground pressure, which further compacts the soil and alters the soil resistance.

Figure 2b shows a tracked vehicle in motion relative to the terrain. A grouser on the track first comes into contact with the ground at position 1. No shearing has occurred at the moment of initial contact. A shearing force develops in the lateral direction as the vehicle moves forward. The grouser position begins to move - pushing against the soil and distorting it (S). The soil distortion increases [1] as the vehicle moves forward.

Figure 2a shows three plots of soil shear stress as a function of soil shear for three different types of terrain conditions [1]. This empirical data is typical of different generic soil types. The curve labeled A is for a loose frictional or plastic soil such as wet clay. The shearing strength τ_a of this

soil type is reached after the initial period of compaction, which takes place



A. Cohesion less Soil
B. Cohesive Soil
C. Mixture of A and B

Figure 2 Characteristics of soil deformation

over a distance S_A . Beyond this point the stress remains nearly the same irrespective of additional slip. Soil type **B** consists of a dry coherent mass: dry clay or snow at very low temperatures. This type of soil quickly reaches its maximum shearing strength and then drops off rapidly. The curve **C** refers to a soil type that has intermediate properties between **A** and **B**. Upon reaching a maximum value, it starts to lose its shearing strength but not as rapidly as **B** [2].

For modeling purposes, it is critical to develop a general equation for these curves. The graphs in Figure 2a correspond to the displacement (x) and natural time frequency (ωt) for an aperiodic vibration:

$$x = A_1 e^{(-b + \sqrt{(b^2 - 1)})\omega t} + A_2 e^{(-b - \sqrt{(b^2 - 1)})\omega t}, \quad (1)$$

where b is the coefficient of damping. An equation describing soil stress assumes the grousers slip during the shearing process. The shearing stress is (τ) and soil deformation (S). We define $\tau = x$,

$K_1 S = \omega t$, and $K_2 = b$ where K_1 and K_2 are coefficients of slippage. Substitution of these parameters gives the following result:

$$\tau = A_1 e^{(-K_2 + \sqrt{(K_2^2 - 1)})K_1 S} + A_2 e^{(-K_2 - \sqrt{(K_2^2 - 1)})K_1 S}. \quad (2)$$

We relate the coefficients A_1 and A_2 by setting $S = 0$ and $\tau = 0$,

$$A_1 + A_2 = 0.$$

Also for $S = 0$, $\tau = 0$, and $d\tau/dS = K_3$,

$$\begin{aligned} d\tau/dS &= A_1 e^{(-K_2 + \sqrt{(K_2^2 - 1)})K_1 S} (-K_2 + \sqrt{(K_2^2 - 1)})K_1 \\ &+ A_2 e^{(-K_2 - \sqrt{(K_2^2 - 1)})K_1 S} (-K_2 - \sqrt{(K_2^2 - 1)})K_1 = K_3. \end{aligned} \quad (3)$$

A_1 and A_2 are given by the following expressions:

$$A_1 = \frac{K_3}{2K_1 \sqrt{(K_2^2 - 1)}} \quad (4)$$

$$A_2 = -\frac{K_3}{2K_1 \sqrt{(K_2^2 - 1)}} \quad (5)$$

Substituting A_1 and A_2 into equation (2):

$$\tau = \frac{K_3}{2K_1 \sqrt{(K_2^2 - 1)}} (e^{(-K_2 + \sqrt{(K_2^2 - 1)})K_1 S} - e^{(-K_2 - \sqrt{(K_2^2 - 1)})K_1 S}) \quad (6)$$

The maximum peak for the curve in Figure 2a is given in equation (7).

$$S_m = \frac{\ln(-K_2 - \sqrt{(K_2^2 - 1)}) - \ln(-K_2 + \sqrt{(K_2^2 - 1)})}{2K_1 \sqrt{(K_2^2 - 1)}} \quad (7)$$

The shear strength (τ) can be defined as the maximum value of the shear stress before the soil yields [3]. Figure 3 contains a Mohr - Coulomb diagram plotting ground pressure as a function of shear stress for any orientation of the reference axis. The Mohr circle expands to a critical size before failure occurs. The line tangential to the failure point is the Mohr-Coulomb failure limit. An equation for this line is $y = mx + b$ where b is the coefficient of cohesion, m is $\tan(\phi)$, ϕ is the frictional angle, and x is normal stress or ground pressure. This line approximates the maximum shearing

strength, τ_m , of a particular soil type, and it is used extensively strength in land locomotion.

$$\tau_m = c + p \tan(\phi) \quad (8)$$

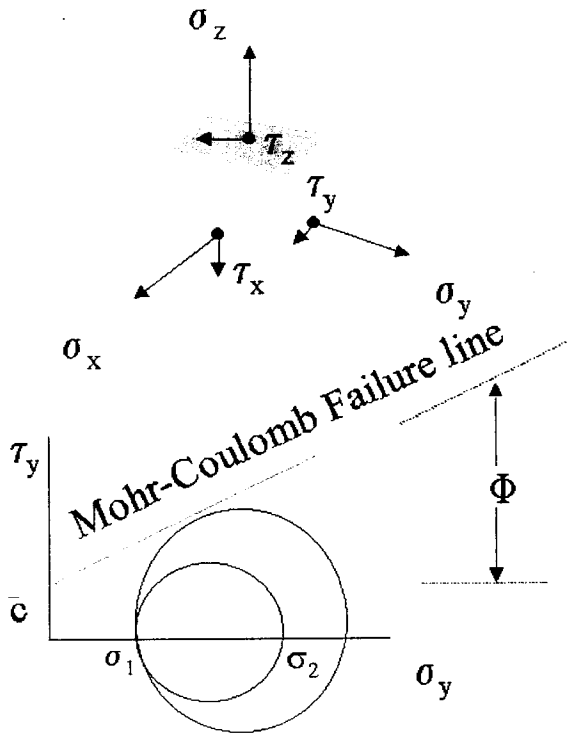


Figure 3 Mohr-Coulomb Failure Line

Since the portion contained in brackets (Eq. 6) is dimensionless, the value of $K_3/2K_1\sqrt{(K_2^2-1)}$ must have the units of lb/in² and the value of K_3 may be expressed in the following manner.

$$K_3 = \frac{2K_1\sqrt{(K_2^2-1)}(c + p \tan \phi)}{[e^{(-K_2+\sqrt{(K_2^2-1)})K_1S} - e^{(-K_2-\sqrt{(K_2^2-1)})K_1S}]_{\max}} \quad (9)$$

Now Eq. (6) can be simplified:

$$\tau = \frac{(c + p \tan \phi)}{y_{\max}} [e^{(-K_2+\sqrt{(K_2^2-1)})K_1S} - e^{(-K_2-\sqrt{(K_2^2-1)})K_1S}] \quad (10)$$

where y_{\max} is the largest value for the expression within the brackets. The slip distortion and the amount of slip are related through the stress strain equations. The maximum shear distance (S_m)

is equal to the product of the slip speed and the time duration in which it occurs.

$$S_m = v_s t \quad (11)$$

However, the slip speed is equal to the difference between the tire or track and actual vehicle speeds:

$$v_s = v_t - v_a \quad (12)$$

$$S_m = (v_t - v_a)t \quad (13)$$

and $t = d/v_t$, where d is the total distance along which the shearing S_m has occurred in contact with the terrain.

$$S_m = d(1 - \frac{v_a}{v_t}) = i_o d \quad (14)$$

The amount of soil distortion that takes place at a distance x from the front of the ground contact area is equal to

$$S = S_m(x/d) \quad (15)$$

$$\text{where,} \quad S = i_o x \quad (16)$$

Equation (16) gives a relationship between tractive force and slip. Figure 4 compares the shear force of a tracked vehicle for two different types of soil. The top graph is highly frictional, undisturbed, firm silt. For 10% slip, shear is produced along the entire ground contact surface; but the front portion of the track produces most of the force [2]. As the vehicle begins to experience more slip, most of the shearing force is produced at the front portion of the track. The rear half of the track produces little shear and increases soil resistance by creating drag.

The second type of soil has a high cohesive property such as wet clay. The track is producing shear forces in relatively equal amounts along its entire length for all percentages of slip.

While in motion, a track or wheel develops a force produced by the shearing strength of the soil. This force H is called the gross tractive effort or soil thrust. The tractive effort is the integral of the shear forces along the slip distance. By substitution of Eq. (10),

$$H = \int_0^d \tau_x dx \quad (17)$$

$$H = \int_0^{y_{\max}} \left\{ \frac{(c + p \tan \phi)}{y_{\max}} (e^{(-K_2 + \sqrt{K_2^2 - 1}) K_1 x} - e^{(-K_2 - \sqrt{K_2^2 - 1}) K_1 x}) \right\} dx \quad (18)$$

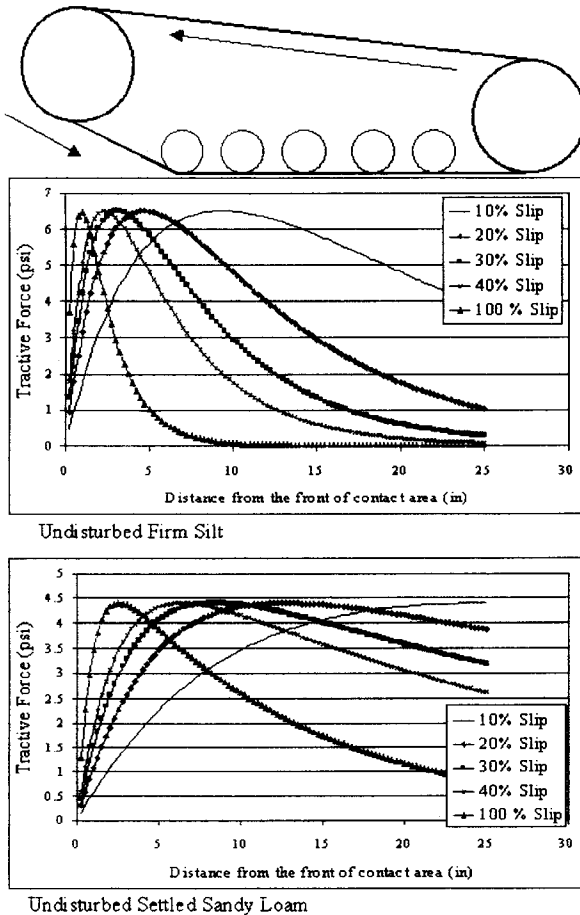


Figure 4 Tractive forces in different soil types

Typically, heavier vehicles are able to generate larger tractive forces. Much experience by a number of investigators over the years gives credibility to this statement, but is it valid for all soil types? In order to answer this question, consider Eq. (19). Soil thrust is defined as the addition of two different soil strengths. The first originates from its frictional properties while the second from its cohesive properties,

$$H = A \cdot c + W \cdot \tan \phi \quad (19)$$

If a soil type such as dry sand is chosen, a homogenous sample would contain no

cohesive properties, Therefore $c=0$, and Eq. (19) is reduced to a single term $W \cdot \tan \phi$. For this case as the vehicle weight is increased the amount of soil thrust increases proportionally.

If the same vehicle is operated in a plastic soil such as saturated wet clay, the frictional component of the soil is equal to zero ($\phi=0$). Equation (19) reduces to $A \cdot c$ where A represents the contact surface area of the vehicle running gear. A higher value of thrust is only obtained by an increase in contact surface area.

In summary, vehicles that traverse highly frictional soils benefit from an increase in ground contact area. Soil types with high moisture content or are very cohesive in nature, improve vehicle mobility with designs that increase ground contact surface area. An increase in weight for this type of soil is a liability [5] resulting in additional soil resistance and compaction.

BDTM SPREAD SHEET

We developed a spread sheet using the Bekker formalism to evaluate robotic vehicle mobility performance. It uses the linear one-degree of freedom (1-DOF) Bekker model that has been created in a spreadsheet format. This model assumes that the soil is homogenous and the loading effects on the soil are linear. Both track and wheeled vehicles can be simulated using this formalism. Important vehicle parameters include tractive force, tractive effort, soil sinkage, drawbar pull, and tractive coefficients (DP/W).

INPUTS

The model inputs are divided into three categories. The first set is general vehicle information. These parameters include the width and length of the track or wheels which are in contact with the ground. These dimensions correspond to the vehicle foot print in contact with the terrain. Other parameters include the number of tracks or wheels, contact area, and vehicular weight.

The second set of inputs describes the vehicle trafficability, or conversely, vehicle performance in a given terrain. These parameters define the strength, sinkage, and slippage that a vehicle would experience in a specific type of homogenous soil. Most of these parameters are obtained from Bevameter measurements, which is a device created by Bekker for this purpose [1]. These measurements

include the depth of the plate sinkage, the modulus of soil deformation in cohesive and frictional soil, the exponent of soil deformation, and the coefficients of slippage. A separate section in the spread sheet provides these parameters for different types of soil. Other parameters such as the coefficient of cohesion and the angle of friction are calculated from the Mohr-Coulomb failure line.

OUTPUTS

The BDTM output parameters are arranged into seven different categories. The first contains the maximum thrust force, which the terrain can support. This parameter is the product of the Mohr-Coulomb maximum ground pressure multiplied by contact area. The Mohr-Coulomb law in Eq. (19) contains the terms $W \cdot \tan \phi$ for the frictional composition of the soil and Ac due to cohesion. Since most terrain is a mixture of these two properties, soil thrust is the sum of these two terms.

The next set of parameters contains soil strength and ground pressure. The vehicle weight produces a normal force and ground pressure on the terrain. The Mohr-Coulomb law determines the maximum soil strength and ground pressure prior to plastic deformation of the terrain. Bekker derived from the stress-strain curves that the soil behavior can be described in terms of the displacement (x) and natural time frequency (ωt) of an aperiodic vibration [2]. The equation for tractive force is derived from this observation, and it is the product of the maximum shear force given by the Mohr-Coulomb Law multiplied by the percentage of slippage between the vehicle and terrain. Equation (18) expresses the tractive effort in terms of soil properties, contact area, load, and slip for a given type of soil defined by the constants K_1 and K_2 .

Bekker derived an empirical formula from his Bevameter experimental data to evaluate sinkage in frictional and cohesive soils,

$$z = \left[\frac{p}{k_c/b + k_\phi} \right]^{1/n}, \quad (20)$$

where p is the ground pressure, b is the minimum dimension of the track or tire, k_c and k_ϕ are frictional and cohesive modulus of soil deformation and n is the exponent of soil deformation. This equation explains why wider tracks or tires on

vehicles with the same ground pressure sink deeper into the terrain.

Not all vehicle soil thrust results in useful work. Instead part of it dissipates into thermal and frictional energy losses, which are caused by compaction, bulldozing, and dragging of the soil. An empirical expression for the losses overcoming compaction resistance may be expressed by

$$R_c = \left(\frac{1}{(n+1)(k_c + bk_\phi)} \right) \left[\frac{W}{l} \right]^{\frac{n+1}{n}}, \quad (21)$$

where W is vehicle weight in pounds and l is the length of the tire or track in contact with the ground. It should be noted from Eq. (21), that longer contact areas produce smaller compaction resistances. Bulldozing results from the accumulation of a soil mass in front of the vehicle tires or tracks. In our analysis the bulldozing resistance is neglected and assumed to be small. Similarly, resistance from soil trapping and dragging is also neglected in our analysis.

The drawbar pull (DP) is the total thrust minus the soils resistances. It is customary to view DP as a primary metric for vehicle locomotion. If it is zero or negative, then the vehicle will have no net forward motion. In BDTM there are three different values for DP. The first considers the soil thrust developed using soil parameters for simple geometric track and tire geometries. The second includes additional thrust that is generated by the action of grousers or treads. The Mohr-Coulomb equation is modified for this result:

$$H = blc(1 + 2h/b) + W \tan \phi \left(1 + 0.64 \left[(h/b) \cot^{-1}(h/b) \right] \right) \quad (22)$$

where b is the width, l is the length, h is the height of the grouser or tire tread, c is the coefficient of cohesion, and ϕ is the angle of friction. The last expression for DP in BDTM is the total tractive force evaluated for a specific percent slip at some distance from the front of the track or tire contact area. A common metric for baseline evaluation normalizes these different expressions by dividing DP by total vehicle weight. These parameters are referred to as traction coefficients, and they are one convenient method for comparing different vehicle types

The final set of outputs is cone index (CI) and mobility index (MI) conversion factors. Waterways Experiment Station (WES) developed a method to measure these soil parameters. The cone index is an empirical parameter, which is measured using a cone penetrometer device. The CI values are obtained by converting Bevameter into CI parameters using Eq. (23) [6]. The conversion was proposed by Janosi [7] and tested by WES in 1964.

$$CI = 1.625 \left(\frac{k}{(n+1)} \left((z+1.5)^{n+1} - z^{n+1} \right) + 0.517k \left(\frac{(z+1.5)^{n+2}}{(n+1)(n+2)} + \frac{z^{n+2}}{n+2} - \frac{(z+1.5)z^{n+1}}{n+1} \right) \right) \quad (23)$$

DATA ANALYSIS

In BDTM there are four different graphing routines. The first plots traction coefficients as a function of k values. This process provides input parameters in the calculation of traction coefficients for different soil strengths. Figure 5 shows both track and wheel versions of the same vehicle in a primarily frictional soil. The tracked vehicle traverses this type of terrain with greater DP than the same system with wheels.

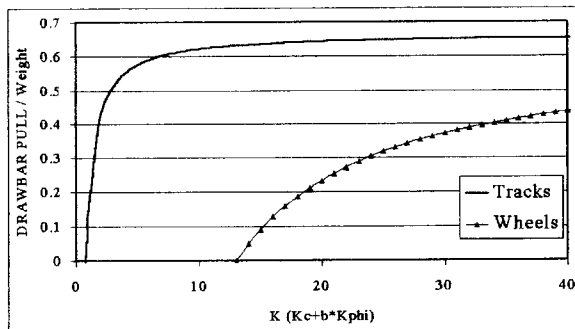


Figure 5 DP/W vs. K values

The next two charts show tractive forces, which are produced for different configurations of track or wheel contact areas.

The calculations in Fig. 6 are made with 10, 20, 30, 40, and 100 percent slip values. Figure 6 shows a tracked vehicle in an undisturbed, settled, sandy loam. The peak tractive forces occur near the front portion of the track for these examples.

Figure 7 displays tractive effort per unit area as a function of percent slip for three different soil types. Type A is a

highly frictional soil that produces nearly all the tractive effort for less than ten percent slippage. Type C on the other hand is a plastic or cohesive soil. Tractive effort is produced relatively uniformly regardless of the soil distortion or slippage experienced.

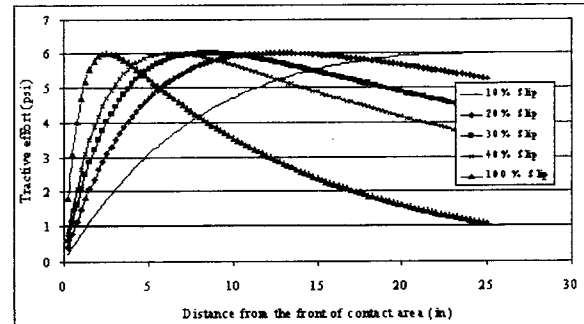
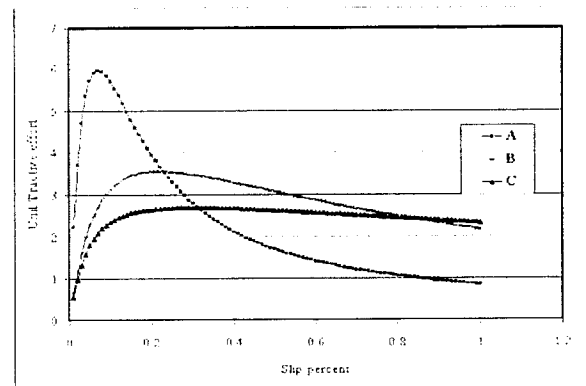


Figure 6 Tractive Forces vs. Distance



- A. Cohesionless or loose frictional soil
- B. Mixture of A and C
- C. Cohesive or plastic soil

Figure 7 Tractive Efforts vs. Slip

EXAMPLES

Two examples in this paper are provided to demonstrate the capabilities of the model.

EXAMPLE 1

The track vs. wheel tradeoff for military vehicle mobility has many different facets. Low-pressure pneumatic tires using adaptive tire pressure can dramatically reduce ground pressure. We will use BDTM to compare this type of wheel running gear system with a vehicle using tracks.

In this section we look at different types of relatively small robotic vehicles

traversing highly cohesive terrain such as wet clay. A small, four-wheel robotic platform with 12" diameter tires is shown in Fig. 8a. The rectangular foot print is 3"x4", weight is 1000 lb. and the tires are separated by a distance of 36". Each tire has a total contact area of 12 sq. in. and an overall surface contact area of 48 sq. in. The ground pressure of the vehicle is 21 psi.

Our model predicts that the wheels will sink 2.3" below the terrain surface. At this depth, the soil resistance is larger than the maximum soil thrust generated by the vehicle. A negative value for DP indicates that the vehicle is incapable of moving forward at a nonzero speed.

One possibility for improving tractive effort might be to increase the net payload or gross vehicle weight. When a 200 lb payload is added to a baseline vehicle weighing 1000 lbs, the wheels sink deeper into the soil. The motion resistance increases and DP remains a negative number. This type of soil is soft and deforms too easily to support the larger ground pressure. This technique does work, however, for more rigid terrains with smaller soil sinkage parameters.

When the diameter of the tire is increased to a 3"x6" foot print as shown in Fig. 8b, the total ground contact area of the vehicle is increased to 72" sq. in. and the soil sinkage is reduced to 1.5". The soil resistance is reduced to a point where the vehicle is now able to move with a positive DP.

In summary an increase in tire diameter, increases vehicle ground contact surface contact area, which ultimately increases platform DP. Additional increases in wheel diameter will ultimately increase the DP to the desired levels. At this point, however, there will be several tradeoffs among various design parameters including turning radius, engine torque and gearing, suspension design and roll over that will limit practical increases in wheel and tire diameters.

An alternative approach might also be to add additional sets of wheels. Figure 8d displays the same robotic platform with a 6x6 wheel configuration. When 12" diameter wheels are used in the design, they produce a 3"x4" foot print. The amount of surface contact area is equivalent to the 4x4 wheel design with the larger tires. By increasing the size of the six tires to allow for a 3"x6" foot print, the platform surface area is increased to 108 sq. in.

The ground pressure decreases to 9.1 psi and the soil sinkage reduced to 1". The net vehicle tractive force increases while the DP doubles in value.

The same platform with a track configuration is shown in Fig. 8c. Each track is 25" long and 3". The ground pressure decreases to 6 psi and soil sinkage to 0.6". The DP increases by a factor of 14 as compared to the original 4-wheeled vehicle, 4x greater than the platform with enlarged tires, 4x larger than the six-wheeled vehicle with 12" diameter wheels, and 2x larger than the six-wheeled vehicle with larger diameter wheels. When an additional 200-lb payload is placed on the tracked vehicle, the tractive effort remains unchanged while the DP decreases somewhat due to additional soil sinkage.

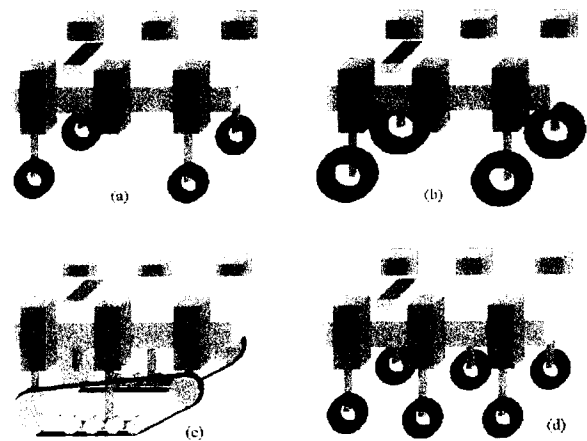


Figure 8 Robotic Vehicles

This example shows some of the mobility tradeoffs that can be made in a plastic soil type such as wet clay. The vehicles ability to traverse in this type of terrain is dependent on the overall design of the running gear configuration and the amount of ground contact surface area.

EXAMPLE 2

This example looks at the tradeoffs between track and wheel running gear for highly frictional types of soil such as dry sand. The same robotic vehicle platforms were also used in this analysis

The tractive force and soil thrust from a vehicle with tires that have a 3"x4" rectangular foot print are comparable to the same vehicle outfitted with a pair of 3"x25" tracks. The track outperforms the tire by a ratio of 1.5/1. If the 4x4 vehicle is outfitted with tires that have

a 3"x6" surface foot print, then this ratio decreases to 1.2/1. The 6x6 vehicle with 3"x6" foot print tires has a ratio nearly equal to 1/1.

An interesting observation from these two examples is that wheel vehicles, which experience more slip relative to the terrain, have performance similar to tracked systems with comparable size and weight. This phenomenon occurs near slip values of 33% slip for the 3"x4" foot print and 24% for the case of oversized tire.

These examples point out another interesting feature of the "wheels vs. tracks" tradeoff. When vehicle payload increases for tracked platforms; the tractive force, soils thrust and DP become larger under some conditions because the ground contact area is sufficiently large to prevent excessive soil sinkage and minimize soil resistance. When payload increases for the 4x4 vehicle, the tractive force and soil thrust both increase less rapidly than the soil resistance. This condition leads to a net reduction in DP. Reducing vehicle payload fraction drastically improves the performance of the wheel relative to the track platforms.

These examples show quite clearly that track running gear mechanisms perform much better than their wheel counterparts for heavy platforms. The larger ground contact areas lead to smaller ground pressures that reduce soil resistance and produce larger tractive forces and net DP. The track systems, however, generate much larger internal frictional losses and are generally less reliability for off road conditions. Light weight wheeled vehicles, however, can perform comparable to track vehicles under many off road conditions assuming the ground pressure is low enough to prevent excessive soil resistance to terrain sinkage. Under these conditions wheel vehicles have many distinct advantages including energy efficiency, maneuverability and agility.

CONCLUSION

This paper explores the Bekker formalism as a methodology to examine mobility tradeoffs between wheel and track platforms. We developed a model, BDTM, as a design tool to compare different types of running gear mechanisms for small robotic vehicle platforms. It is a simple, linear one-degree of freedom (1-DOF) model that has been created in a spreadsheet format.

We use BDRM primarily as an analytical tool for off-road vehicle mobility performance evaluation. This methodology supplements the NATO Reference Mobility Model (NRMM), which is the Army's primary mobility performance evaluation tool for off road platforms. The NRMM model is inherently empirical in nature, and its foundation rests upon a huge historical data base that has been acquired over many years. The Bekker model, although simplistic in its formulation, is easy to use and provides a phenomenological understanding of many essential features in vehicle terrain mechanics.

Our particular interest in the Bekker Model involves performance evaluations of small, unmanned ground vehicle systems that weigh under 1500 lbs. Most empirical data bases have very little data for this size and weight class of vehicles. The Bekker model has been very useful in making rudimentary design tradeoffs for very small platforms weighing 100 pounds or less where very little empirical data is available. One can calculate tractive force, tractive effort, drawbar-pull, soil sinkage, safe weight pressures, ground pressures, and percent slippage for these systems.

REFERENCES

1. Bekker, M.G. 1960 *Off-the-Road Locomotion* University of Michigan Press, USA
2. Bekker, M.G. June 1955 "Wheels or Tracks" *Automobile Engineer*
3. Whitlow R 1990 *Basic Soil Mechanics* (2nd Ed) Longman Group, UK p207
4. Wong, J.Y. 1989 Elsevier Science Publisher B.V., The Netherlands
5. Bekker, M.G. Land Locomotion Research Report 13, 1957 "Terrain Evaluation in Automotive Off-the-Road Operations" OTAC, Detroit
6. Bekker, M.G. 1969 *Introduction to Terrain-Vehicle Systems* University of Michigan Press, USA
7. Janosi, Z and Hanamoto, B. 1961, Proc. Of the 1st International Conference on the Mechanics of Soil-Vehicle Systems, Edizioni Minerva Tecnica, Torino, Italy.